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by

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Danish Atomic Energy Commission
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Abstract

At the Danish 5 MW research reactor DR 2, a reactor power indicating instrument has been developed, whose design is based upon the measurement of the N^{16} gamma activity in the light water coolant from the core. The instrument consists of a NaI(Tl) scintillation counter together with a single channel analyzer, which when adjusted to an energy of app. 4 MeV measures only the high energy γ-radiation from N^{16} ($E = 6.1$ MeV and 7.1 MeV; $t_{1/2} = 7.35$ sec) in the primary coolant. The instrument is equipped with a counter which in addition to indicating the reactor power level gives a direct indication of integrated reactor power in MW-hours.

By adjusting the shielding and geometry of the detector, it has been possible to obtain that a part of the gamma spectrum at the detector position is hyperbolic in shape. It is shown that when the single channel analyzer is measuring at this section of the spectrum, errors in the indication of reactor power due to variations in the gain of the photomultiplier and amplifier are eliminated.

In addition, the influence from flow-rate upon the indication of reactor power by the N^{16} measuring instrument has been eliminated over the usual variations of flow rate by proper positioning and shielding of the scintillation crystal.

The operating experience with this measuring instrument has proved that it gives an indication within ±1% of the power as determined from thermal measurements and for all practical purposes independent of core-configurations, control rod positions and temperature of the primary coolant.

Introduction

The DR 2 is a tank type 5 MW research reactor moderated and cooled by light water. The reactor was built by the Foster Wheeler Corp., New York, and began operation in December 1958.

At DR 2, the reactor power level was originally indicated by compensated, boron ionization chambers which were calibrated in terms of thermal power by a measurement of the primary coolant flow rate and the temperature rise in the core.

It is well known, however, that this method of power indication is far from ideal and, therefore, an investigation was made of other methods. Among these, one of the most promising seemed the measurement of the radiation from N^{16}, a short-lived activity which is produced in the water coolant almost exclusively by the reaction $O^{16}(n,p)N^{16}$ during its passage through the reactor core (ref. 1).

The N^{16} activity has two characteristics which makes it particularly well suited for indicating the reactor power level. First, the half life is 7.35 seconds, which allows the measurement to respond quickly to a change in power level; and secondly, the quantity of N^{16} in the coolant can be determined by measurement of the 6.1 MeV and 7.1 MeV gamma rays from this isotope which are considerably more energetic than those of other activities found in the coolant (see ref. 2).

The threshold of the $O^{16}(n,p)N^{16}$ reaction is exceptionally high ($\sim$ 9 MeV); and therefore, the production of N^{16} depends only upon the total exposure of the coolant to fission neutrons. This means that the N^{16} activity only depends upon the fission rate and hence the reactor power level. Therefore, contrary to power indicating instruments, measuring the thermal neutron flux in the core, an instrument based on the detection of the N^{16} activity of the coolant will be insensitive to variations in the ratio between fission rate and thermal neutron flux, which for instance can be caused by fuel burn-up and temperature changes.

A power indicating instrument based on the detection of N^{16} was installed at DR 2 in order to study its behaviour.

The Reactor and Its Conventional Power Indication

The arrangement of the reactor core and one of the compensated ionization chambers in the conventional instrumentation for power indication is shown in fig. 1. The core consists of MTR type fuel elements containing uranium enriched to 90% content of U-235. The reactor is controlled by five B_4C filled shim-safety rods and one stainless steel regulating rod.

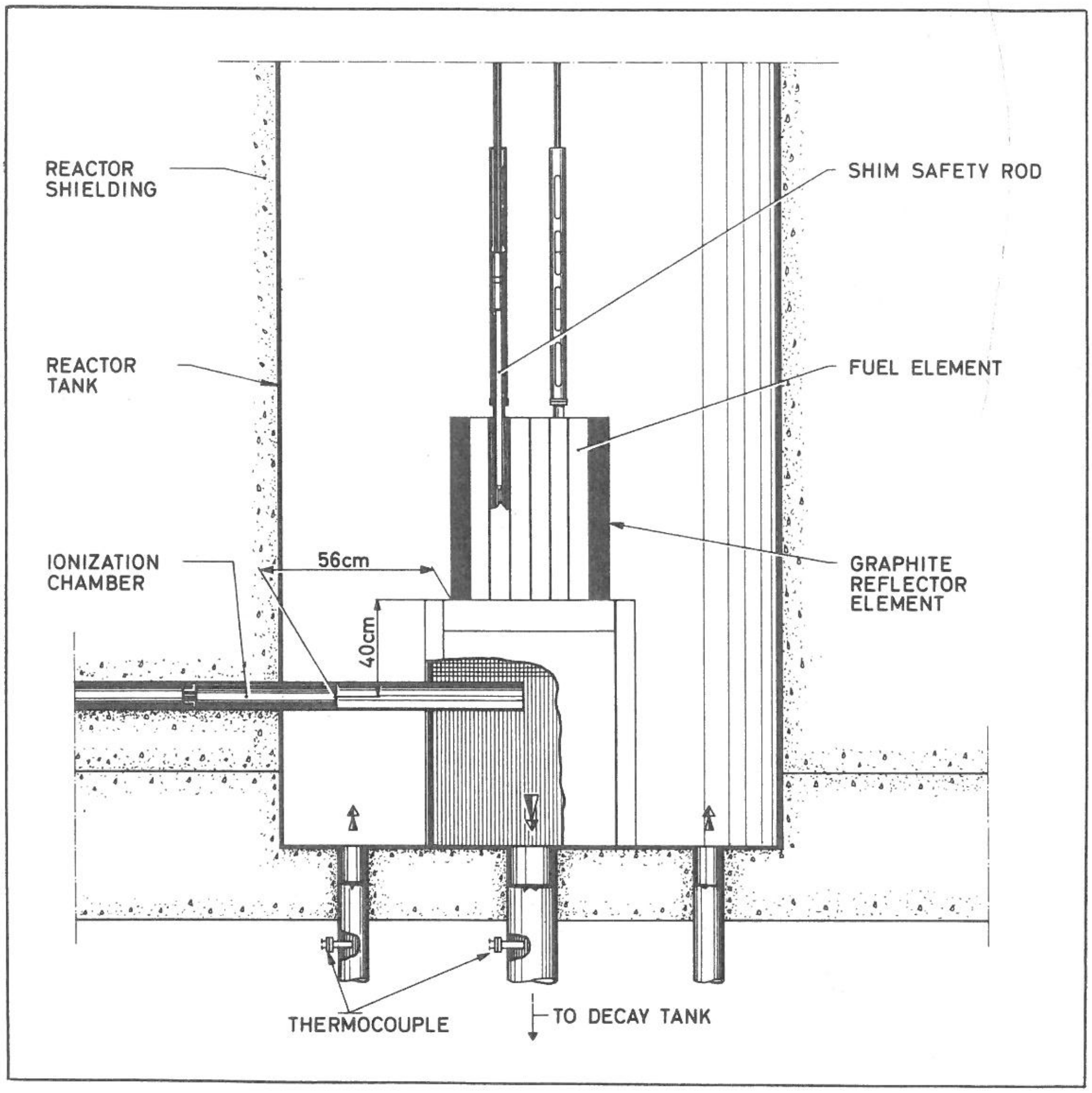

Fig. 1. Vertical section through the reactor core.

The reactor coolant, as shown in fig. 2, flows downwards through the core and from there to a shielded decay tank, which introduces a delay of about 110 seconds into the coolant flow line to permit the decay of short-lived activities, mainly N^{16} (ref. 2). From the decay tank, the coolant flows to the circulating pumps, heat exchangers and back into the reactor tank. At normal flow rate (0.1 m^3/sec) the total recycling time of the primary circuit is app. 250 seconds.

The power indicating instruments are calibrated in terms of thermal reactor power, determined by the product of primary coolant flow rate and temperature rise in the core during stationary conditions. The temperature rise of the coolant is measured by means of precision-calibrated thermocouples near the inlet and outlet of the reactor tank (see fig. 1), and the flow rate by the pressure drop across an orifice in the primary pipesystem. The determination of the thermal power is made at a time

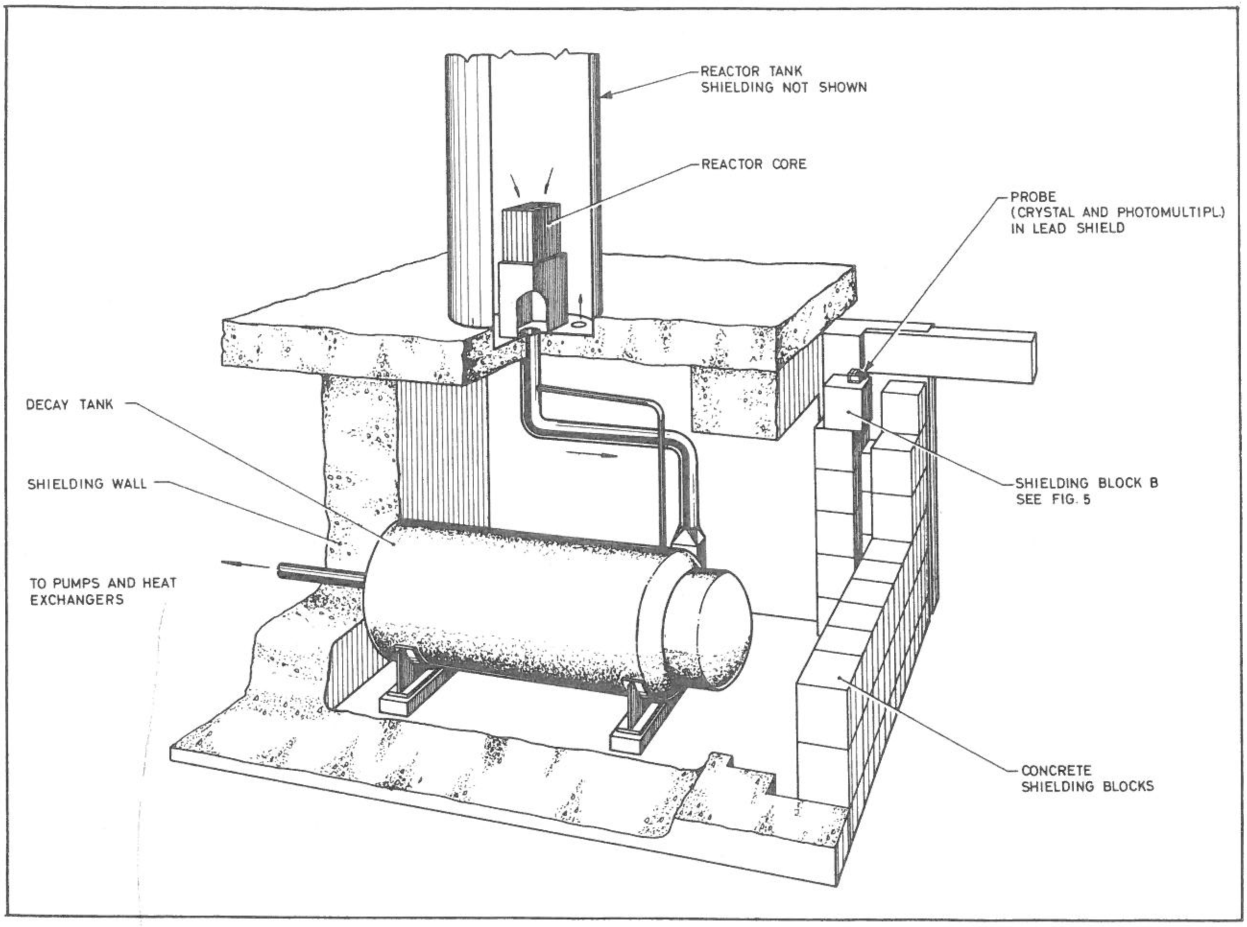

Fig. 2. Location of the decay tank and its connections to the primary cooling system.

when the heat production from fission products in the core has reached, for all practical purposes, the equilibrium value which as known is proportional to the reactor power level. An estimate of the heat losses to the surroundings from the part of the primary water circuit which is between the thermocouples (i.e. the reactor tank) has indicated that these losses are negligible; therefore, the above calculated thermal power is proportional to the fission rate in the reactor core.

The conventional instruments for power indication at DR 2, however, suffer from the disadvantage that their calibration in thermal power vary appreciably when the operating conditions of the reactor are changed. It has been found that even small changes in the core configuration cause considerable variation in the calibration. For instance, a replacement of only a single graphite reflector element by a standard fuel element at the side of the core which faces the ionization chamber causes a change in the calibration of app. 3%.

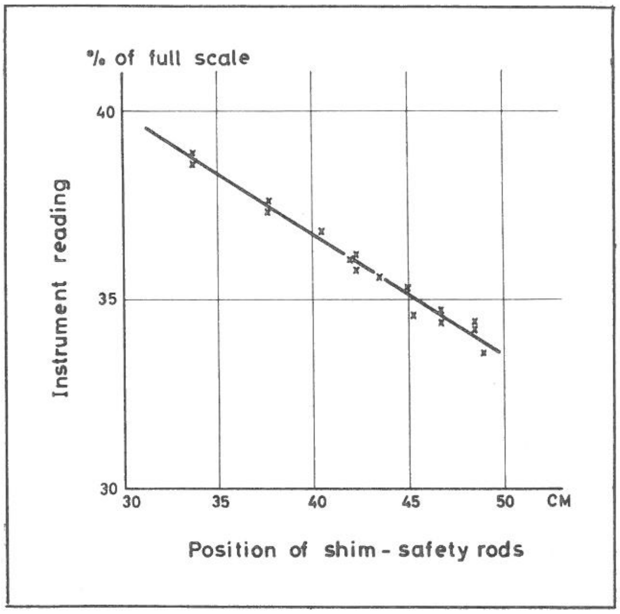

Fig. 3. Power indication by an ionization chamber instrument vs. position of shim safety rods at a constant thermal power of 5 MW.

Movement of the control rods also changes the thermal power calibration of these instruments due to the accompanying displacement of the neutron flux in the direction towards or away from the ionization chambers. Figure 3 shows the reactor power indicated by one of the ionization chamber instruments at DR 2 vs. position of the shim-safety rods at a constant thermal power of 5 MW. It is seen that in the normal operating range of the control rods (between 35 and 50 cm from the position at shut-down) a variation in control rod position of 1 cm causes a change of 1% in the calibration. The temperature level of the primary coolant has also proved to influence the calibration in thermal power of the instruments. Observations have shown that a variation of $5^{o}C$ of the temperature level of the primary coolant causes the calibration to change app. 2%. A two-group calculation (ref. 3) has shown that this effect is due to the variation in the shielding properties of the water between the ionization chamber and the core, arising mainly from the changes of the water density which accompany the temperature variations. Since the distance between core and ionization chamber is relatively great ("average" distance $\approx$ 100 cm, see fig. 1), a variation in the density of the water will considerably change the intensity of the radiation at the ionization chamber. The result of the two-group calculation has been confirmed by measurements taken at two different coolant temperatures, of the activation of indium foils placed near the ionization chamber and in a neutron beam from the reactor surface, respectively.

Description of The N^{16} Measuring Instrument

The N^{16} instrument consists of a scintillation counter and a single channel analyzer. The detector is a 2" x 2" NaI(Tl) crystal which is mounted in a probe together with a photomultiplier and a cathode follower. This probe can be placed at different positions where N^{16} activity from the primary coolant can be detected. The high voltage supply, linear amplifier and pulse height analyzer are located in the experimental basement of the reactor. All components are supplied from a constant voltage transformer.

The pulses from the analyzer are recorded both by an electronic counter and by a ratemeter in the control room. Every 10,000th pulse from the electronic counter is transferred to a mechanical counter. The ratemeter is connected to a pen-recorder. The N^{16} measuring instrument indicates the reactor power level by the above-mentioned ratemeter, and integrated reactor power by the counter.

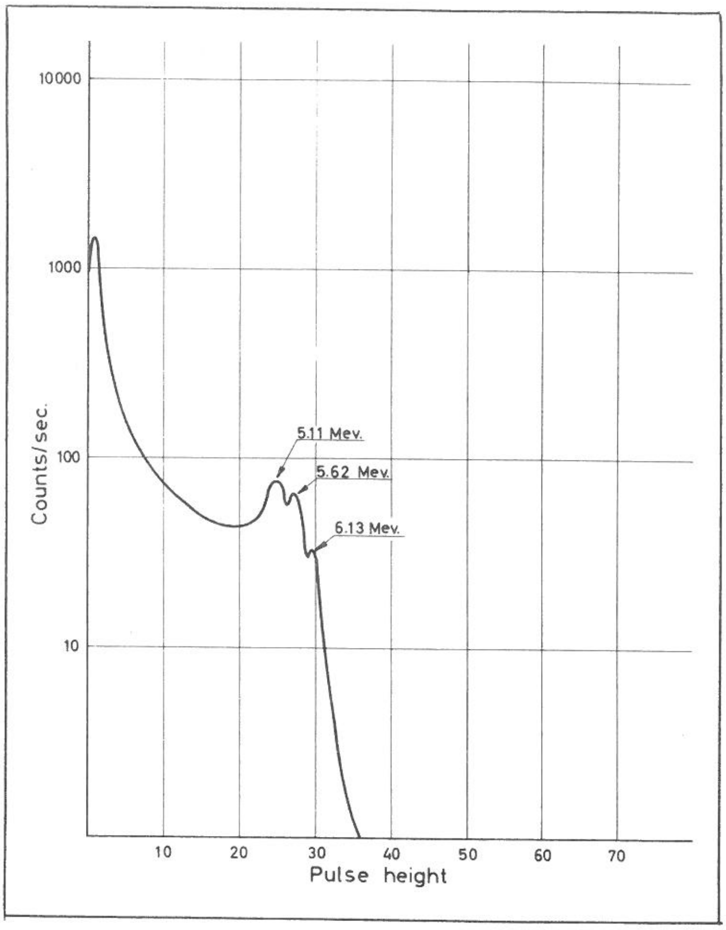

Fig. 4a. Gamma-ray spectrum within the decay tank shielding. Reactor power 20 kW.

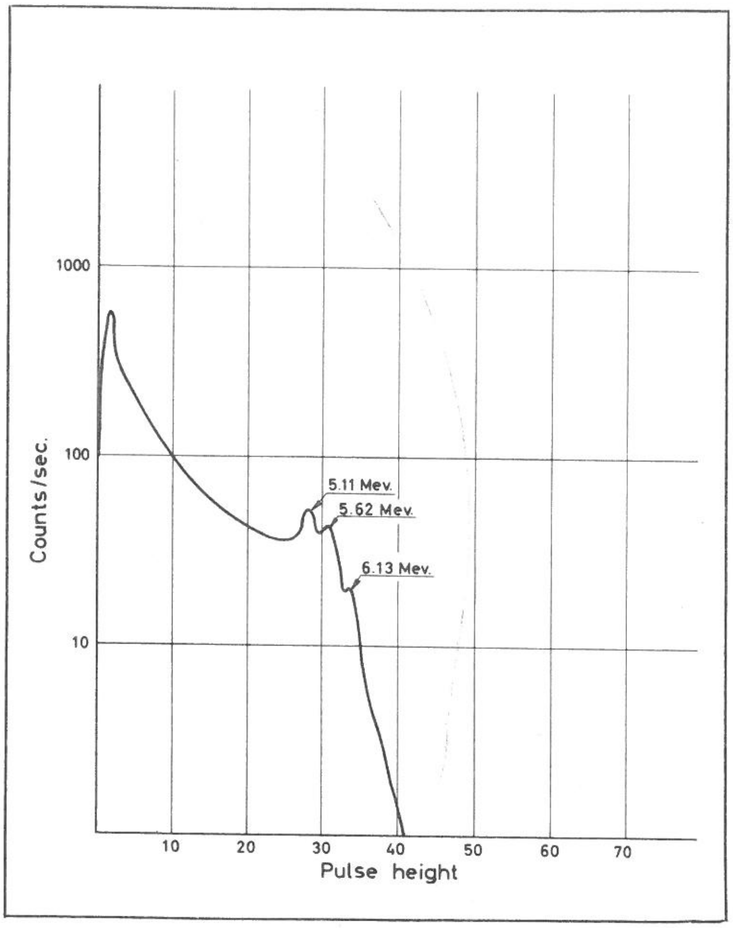

Fig. 4b. Gamma-ray spectrum on top of shield block B, see fig. 2. Reactor power 5 MW.

Figure 4a shows a γ-spectrum measured with the probe placed in the decay tank room. In order to obtain a sufficiently low radiation intensity at the position of the probe, the reactor was operated at a power level of 20 kW, and, in addition, two 5 cm thick lead blocks with an aperture of 4 mm were placed in front of the detector. The peak at the highest energy corresponds to 6.13 MeV. At lower energy the corresponding one and two annihilation gamma, escape peaks can be seen.

Because of the high radiation level in the decay tank room, it was impossible to make measurements at a power level of 5 MW. A radiation area of suitable intensity was found on top of the concrete shielding blocks around the decay tank where one of the blocks (block B, see fig. 2 and fig. 5) has been withdrawn 20 cm.

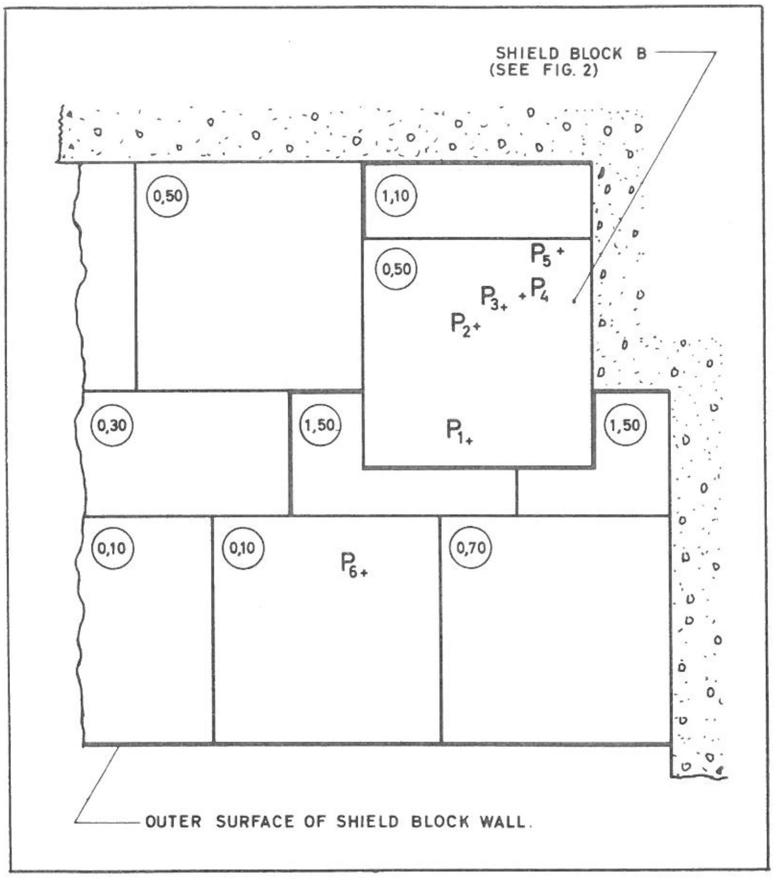

Fig. 5. Partial view of horizontal section in the shield around the decay tank. P_1 – P_6 indicate various positions of the probe. The figures in the circles indicate distance (in metres) between the concrete block and the ceiling.

In order to determine the spectrum of the γ-radiation at this point, a measurement has been carried out at 5 MW with the probe placed on the edge of concrete block B. The γ-irradiation intensity was 0.5 R/h; and, consequently, it was necessary to shield the detector with a 5 to 10 cm lead house containing a rather small entrance aperture. The spectrum is shown in fig. 4b. The peaks in this spectrum do not appear as distinctly as the peaks in the spectrum at fig. 4a, since the proportion of scattered radiation is comparatively larger.

As mentioned the measuring instrument described here is based on the principle that it measures the γ-radiation of N^{16} and excludes any other radiation from the coolant. Fig. 6 shows the normal γ-spectrum for operation at 5 MW as well as two spectra measured 10 min. and 60 min. after shut-down, re-

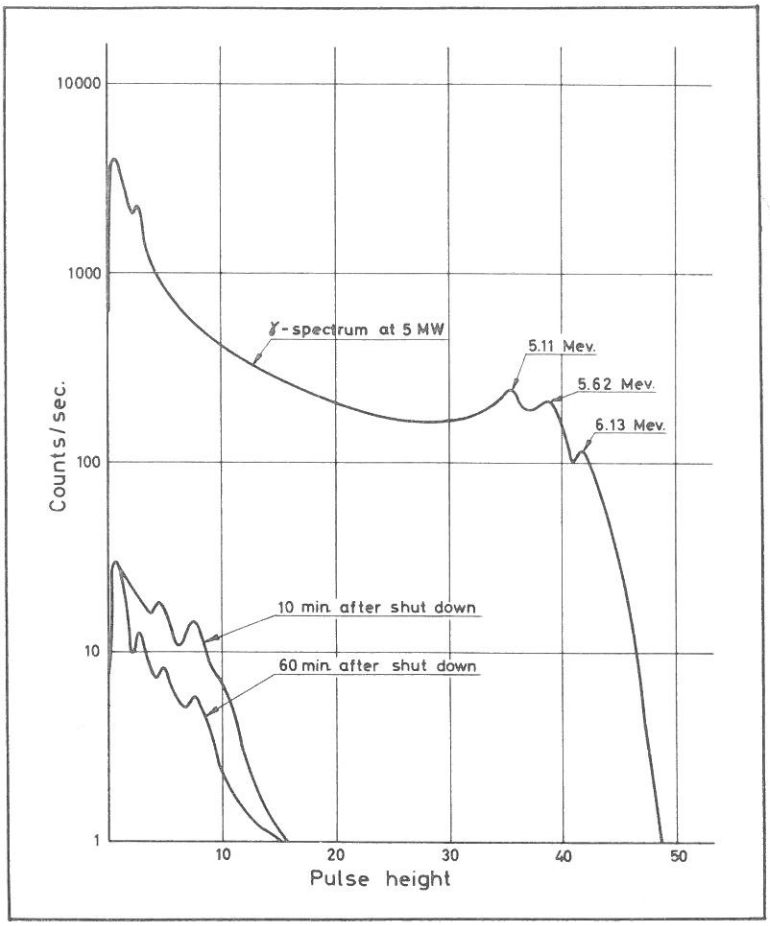

Fig. 6. Spectrum of gamma-rays from coolant at 5 MW, 10 min. and 60 min. after shut-down, respectively.

spectively. Before shut-down the reactor had been in continuous operation for 32 hours at 5 MW. It can be observed that the instrument will measure only the short-lived radiation from N^{16} if the pulse height analyzer is adjusted to discriminate at 3 MeV or higher.

The following two measuring methods can now be considered:

1. The single channel method, in which pulse heights in a chosen interval are counted.
2. The fixed bias method, where all the pulses above a certain height are counted.

In particular, it is a question of obtaining stability against changes in the gain of the photo-multiplier and amplifier. Therefore, the dependence of the two measuring methods on the amplification was investigated further.

1. The single channel method:

We assume that the γ-spectrum is given by the function

$$y_1 = f(x)$$

The spectrum will, by an increase of the amplification by a factor (a), be given by the function

$$y_2 = \frac{1}{a} f(\frac{x}{a})$$

In case the spectrum has the shape of a hyperbola $y = k \cdot \frac{1}{x}$, where k is a constant, it is seen directly that for all x:

$$y_1 = y_2$$

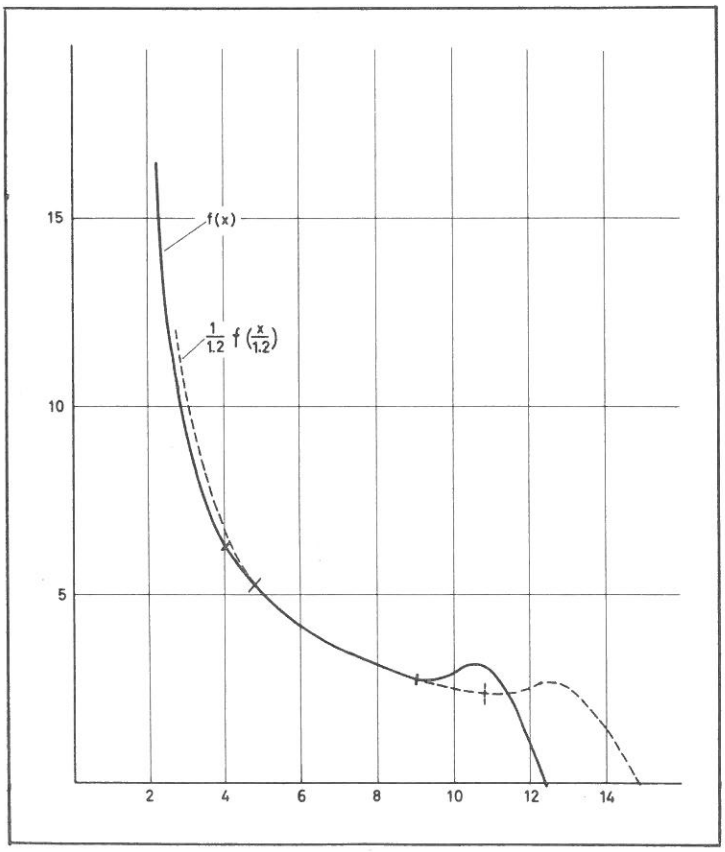

Fig. 7. Effect upon a gamma-ray spectrum of a 20% increase in amplification.

Thus, it is important to choose a section of the gamma spectrum which is approximately hyperbolic in shape in order to make the response of the instrument independent of gain.

Fig. 7 shows a spectrum, y = f(x), which is hyperbolic from about x = 4 to about x = 9, and in the same diagram the function 1/1.2 f (x/1.2) is drawn which is the spectrum to be measured if the amplification is increased by a factor of 1.2. The function 1/1.2 f (x/1.2) is hyperbolic from about x = 4.8 to about x = 10.8. As it is seen, the two functions coincide from about x = 4.8 to about x = 9. If a single channel analyzer was adjusted to measure within this range, the counting rate would not have been affected by the 20% increase of amplification.

In order to find a place near the decay tank where the spectrum of the γ-radiation is hyperbolic in shape at the largest possible energy interval, a number of measurements have been made at different positions and with different shieldings.

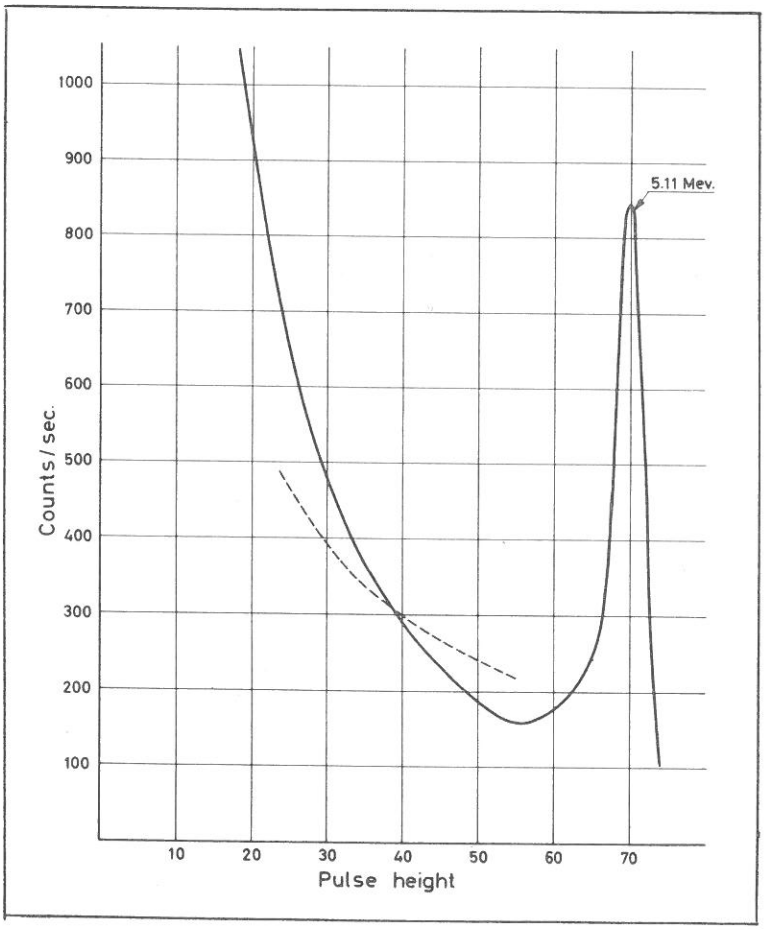

Fig. 8. Gamma-ray spectrum at P_6 (see fig. 5).
No lead shield around the probe.

In the present case it is possible to change the shape of the γ-spectrum of the radiation reaching the detector. This can be done partly by changing the ratio between direct radiation and scattered radiation, and partly by surrounding the probe with shielding which will affect the hard and soft radiation differently.

The spectrum in fig. 8 is made while the detector was placed at point P_6, see fig. 5, at such a large distance that it was unnecessary to use lead shielding. In the diagram a hyperbola is drawn and it is seen that there is too much radiation at low energy.

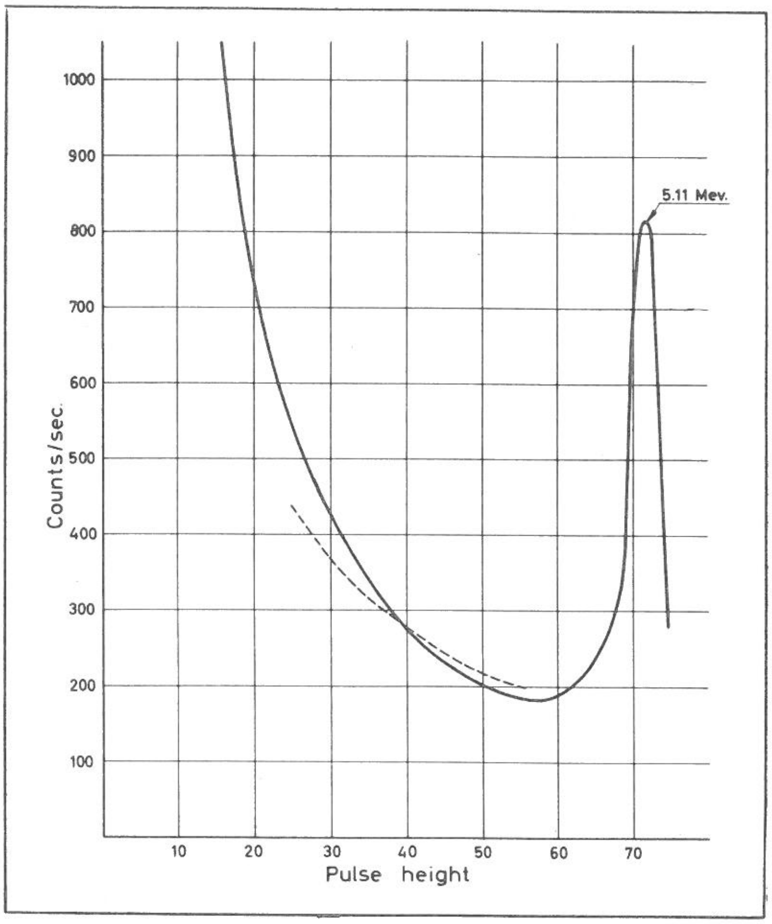

Fig. 9. Gamma-ray spectrum at P_2 (see fig. 5). Probe shielded by 2.5 cm lead.

The spectrum in fig. 9 is made while the detector was placed on top of block B in position P_2, see fig. 5. A lead shielding of 2.5 cm lead was placed around the detector. Due to the better shielding of the house for low energy gammas as well as the decrease of the ratio between scattered and direct radia-

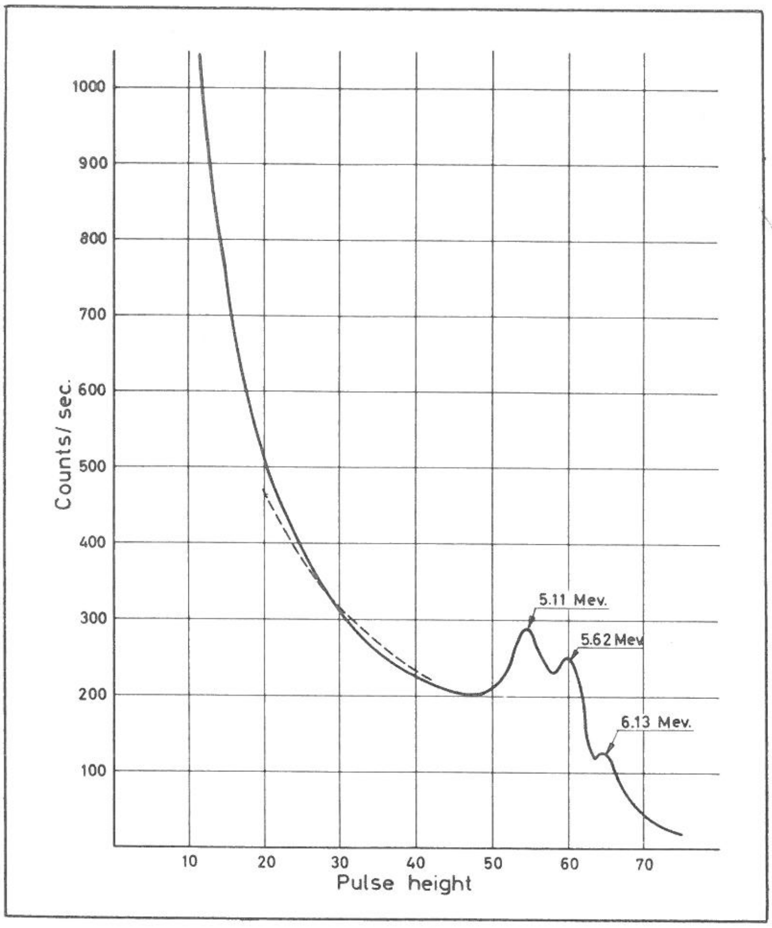

Fig. 10. Gamma-ray spectrum at P_3 (see fig. 5). Probe shielded by 5-10 cm lead.

tion when approaching the source, this spectrum is a better approximation to a hyperbola.

In order to improve the conditions, a lead house with a wall thickness of 10 cm towards the radiation was built, the other walls were 5 cm. The lead house had been moved forward so that the position of the detector was point P_3, see fig. 5. The radiation level at this point is 0.5 R/hr. Fig. 10 shows the spectrum at P_3, made with a channel width of 1.5 volts. This spectrum represents the best approximation to a hyperbola, which it has been possible to obtain.

In order to verify the stability of the instrument to variations in amplification, the count rate was plotted vs. high voltage at a constant reactor power level of 5 MW; the single analyzer was adjusted to a pulse height of 35 volts and a channel width of 6 volts. The result is shown in fig. 11. A variation of

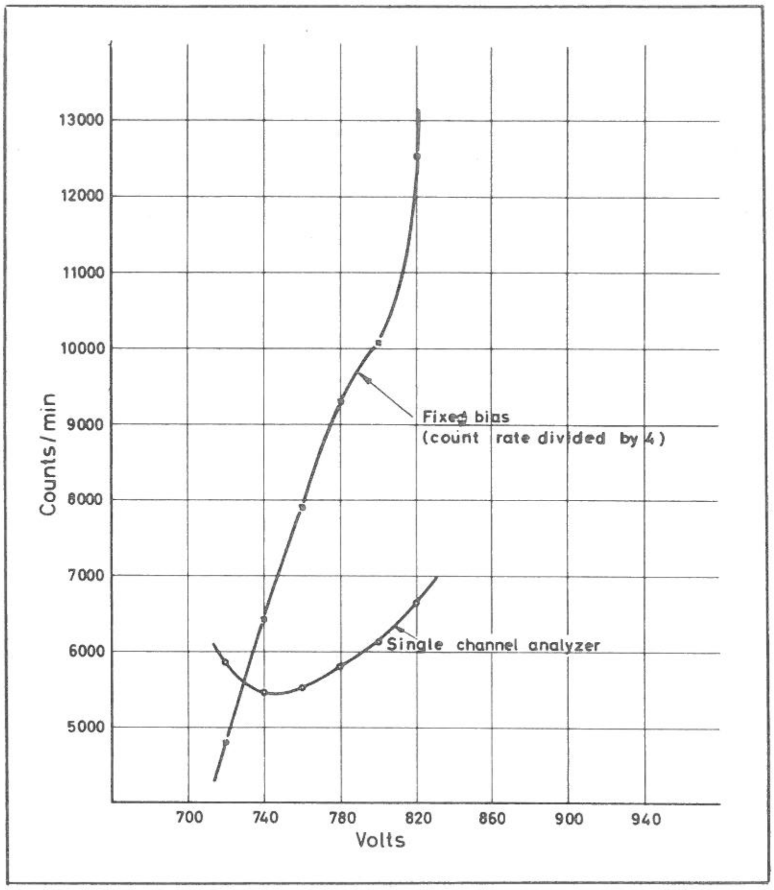

Fig. 11. Count rate vs. high voltage for the "fixed bias" method and the single-channel-method.

the high voltage from 720 volts to 820 volts causes an increase of the amplification by a factor of 2.4, but as seen from fig. 11 this only gives rise to a relatively small variation in the count rate.

2. Fixed bias method:

In order to investigate the stability of the instrument to variations in amplification, when the fixed bias method is employed the same plotting of count rate vs. high voltage was made. The threshold was placed at 35 volts ($\sim$ 3.2 MeV).

The result is shown in fig. 11. (Note that in this case, all ordinates are reduced by a factor of 4).

As seen from fig. 11 the count rate is considerably more independent of the amplification of the detector electronics by the single channel method than by the fixed bias method.

The pulse height analyzer in the N^{16} instrument is, therefore, employed as a single channel analyzer. In accordance with figs. 10 and 11 it is adjusted to a pulse height of 35 volts with a high voltage of 750 volts in order to obtain the maximum possible stability of the detector electronics. The width of the channel is adjusted to such a size that the count rate is 500000 pulses per hour at a reactor power level of 5 MW in order that the counter gives a direct indication of integrated reactor power in terms of MW hr.

The sensitivities of the ratemeter and recorder are adjusted so that the measuring range is 0-10 MW.

Influence of The Flow-Rate upon Power Signal from The N^{16} Measuring Instrument

A power measuring instrument, based upon measurement of a coolant activity has the inherent disadvantage that its power signal is dependent upon the flow-rate of the coolant. However, as described below, it has been possible to eliminate this disadvantage of the N^{16} measuring instrument at DR 2 for normal reactor operation.

The dependence on flow-rate of the power signal from the N^{16} measuring instrument can be derived from the equations for an activity which is induced into a reactor coolant (ref.4). The specific activity A(P) in (dis/cm^3) of the primary coolant at a point, P, in the circuit is approximately given by an expression of the form[x)]

$$A(P) \cong K \cdot N_o \cdot \emptyset_f \; (1-e^{-\lambda\tau}) \cdot e^{-\lambda t_p} \qquad (1)$$

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x) Compare eq. (9) in ref. 4, page 93.
This equation is applicable for this case, since for DR 2 at full power:
$\emptyset_f \cong 10^{10}$ n/cm^2 and σ, the corresponding cross section for the $O^{16}(n,p)N^{16}$ reaction, is $\cong 5 \cdot 10^{-26}$ cm^2 and hence $\sigma \emptyset_f \ll \lambda = 0.0943$ sec^{-1}.

where: K = a constant

N_o = number of O^{16} atoms per cm^3 of coolant

$\emptyset_f$ = average neutron flux in the core above threshold for the $O^{16}(n,p)N^{16}$ reaction (n/cm^2sec)

λ = decay constant of N^{16} (sec^{-1})

τ = time of activation in the core (sec)

t_p = average age at P of N^{16} atoms, created in the core, reckoned from core outlet (sec)

Formula 1 involves the assumption that the activation of the coolant which takes place within the core is a constant fraction of the total activation of the coolant and consequently that the total coolant activation is proportional to the activation within the core, which for this application is a sufficiently accurate approximation (ref. 4, chapter 4). Since, as mentioned above, the recycling time is app. 250 seconds (34 times $t_{1/2}$ for N^{16}), no correction for reactivation of the coolant is necessary.

In order to examine the dependence of A(P) upon the flow rate, Q, we transform eq. (1) to the following:

$$A(P) \cong K \cdot N_o \cdot \emptyset_f \left(1-e^{-\lambda\frac{V_c}{Q}}\right) \cdot e^{-\lambda\frac{V_p}{Q}} \qquad (2)$$

where: Q = primary coolant flow rate (m^3/sec)

V_c = volume of water in the core (m^3)

V_p = effective volume of water in the primary circuit between core exit and the point P (m^3)

By differentiating eq. (2) with respect to Q, we get

$$\frac{\partial A}{\partial Q} \cong K \cdot \emptyset_f \cdot N_o \cdot \frac{\lambda}{Q^2} \cdot e^{-\lambda\frac{V_p}{Q}} \left(V_p - e^{-\lambda\frac{V_c}{Q}} (V_p + V_c)\right)$$

After expanding the exponential $e^{-\lambda\frac{V_c}{Q}}$ and retaining only first order terms, we obtain:

$$\frac{\partial A}{\partial Q} \cong K \cdot \emptyset_f \cdot N_o \cdot \frac{\lambda^2}{Q^2} \cdot V_c \cdot e^{-\lambda \frac{V_p}{Q}} \left(\frac{V_c}{Q} + \frac{V_p}{Q} - \frac{1}{\lambda}\right)$$

$$= K \cdot N_o \cdot \emptyset_f \cdot \frac{\lambda^2}{Q^2} \cdot V_c \cdot e^{-\lambda \frac{V_p}{Q}} \left(\tau + t_p - \frac{1}{\lambda}\right) \qquad (3)$$

When numerical values are inserted in this equation, it is found that, under normal operating conditions, the point where $\frac{\partial A}{\partial Q}$ has a zero value is situated in the beginning of the decay tank. At points nearer the core $\frac{\partial A}{\partial Q}$ is negative and at points further away $\frac{\partial A}{\partial Q}$ is positive. This variation in $\frac{\partial A}{\partial Q}$ is due to the fact that the influence from variations in flow rate at any point is a "competition" between the influences upon activation and decay. These have opposite sign and both vary in size along the circuit.

This effect has been demonstrated experimentally at DR 2. In agreement with equation (3), measurement of the N^{16} radiation from various parts of the primary circuit has shown that

(1) $\frac{\partial A}{\partial Q}$ is negative at points near the inlet to the decay tank, where $\tau + t_p < \frac{1}{\lambda}$

(2) $\frac{\partial A}{\partial Q}$ is positive near the outlet from the decay tank, where $\tau + t_p > \frac{1}{\lambda}$

The scintillation probe of the N^{16} channel is placed in the vicinity of the decay tank as shown in fig. 2, and, therefore, it will receive a mixture of the radiation from the various sections of the decay tank that have different shielding and geometry relative to the probe.

It can be seen that by proper arrangement of the shielding and geometry between probe and decay tank, it should be possible to place the probe in such a manner that an increase of the flow rate within a certain range will cause the increases in the signal from the probe, arising from sections with positive $\frac{\partial A}{\partial Q}$ to cancel out the decreases originating from other sections with negative $\frac{\partial A}{\partial Q}$. In that case the count rate will be independent of flow rate in the flow interval concerned.

An adjustment of this kind has been made at DR 2 and it has appeared to be a very simple matter since it was accomplished simply by moving the scintillation probe back and forth on the shielding block where it is placed (shield block B, see fig. 2). Table I shows for the different positions of the probe P_1 - P_5 on top of shield block B (see fig. 5) the percentage variation in the signal from the probe caused by a change in the primary coolant flow rate from 5.95 m^3/min to 7.40 m^3/min, which are the limits for normal reactor operation.

Table I

Position	P_1	P_2	P_3	P_4	P_5
Variation in signal	+ 9%	+ 3%	+ 1%	+ 0%	- 5%

On the basis of these measurements the scintillation probe was then placed permanently at P_4 (see fig. 5), and, therefore, as seen from Table I, the signal from the probe and hence also the indication of power level by the N^{16} measuring instrument is independent of the flow rate when this is kept within its normal range.

Experience with The N^{16} Power Measuring Instrument

The N^{16} power measuring instrument was installed at DR 2 in January 1961. After the instrument had been adjusted to the maximum stability to variations in high voltage as well as flow rate, as described above, the indication of reactor power has remained within $\pm$ 1% of the thermal power as measured in the previously described manner by the heat, which is released to the coolant.

It has been found that the power indication varies linearly with the thermal power in accordance with eq. 1 since, as known, $\varnothing_f$ is directly proportional to the fission rate. Fig. 12 shows the calibration of the N^{16} measuring instrument vs. thermal reactor power.

During the period of operation of the N^{16} instrument it has not been necessary to make any corrections to its cali-

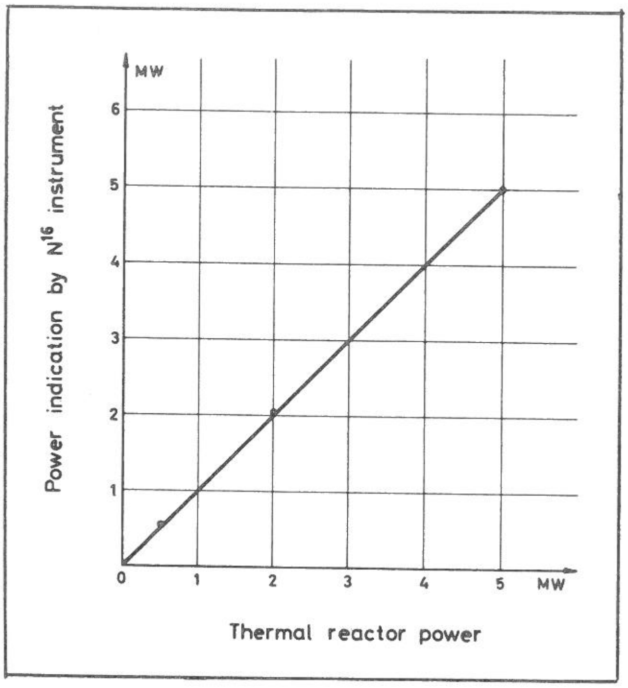

Fig. 12. Power indication by the N^{16} measuring instrument vs. thermal reactor power.

bration in thermal power although the operating conditions of the reactor have been varied considerably. For example, the core size has been increased by app. 10% as a compensation for fuel burn-up; the control rods have been moved through their entire operating range from 34 cm withdrawal to 50 cm withdrawal from the shut-down position and the temperature level of the coolant has been varied $\pm$ 5°C. Furthermore, the concentration of radioactive isotopes other than N^{16} has varied considerably during the operating cycles of the reactor; but due to the previously described high energy discrimination with the pulse-height analyzer, no other isotopes which normally occur in the coolant have influenced the power signal.

However, if the operating conditions vary extremely, some corrections of the thermal power calibration of the N^{16} instrument will be necessary. For instance, if the maximum, resp. minimum possible cores were built, it has been calculated by means of eq. 1 that the calibration would change 1.6% and 1.8%, respectively, relative to the present calibration. The variation of the calibration can be explained as follows (see eq. 1): A variation of the core size by a certain factor, F,

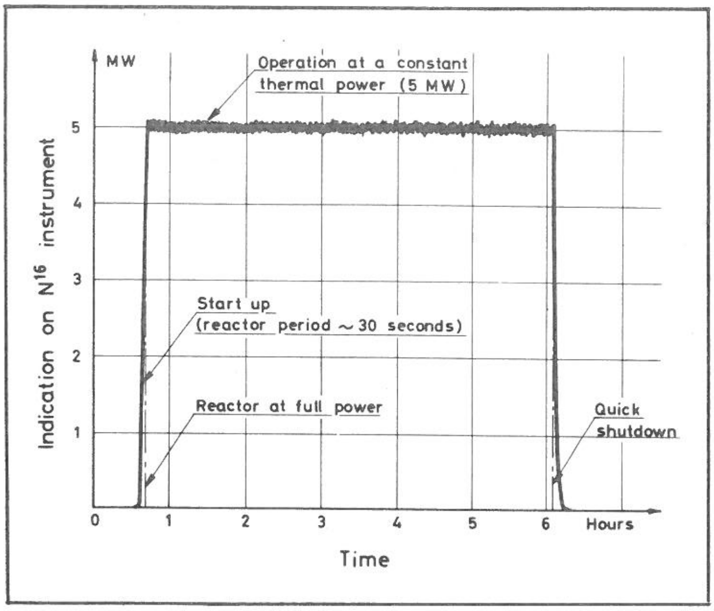

Fig. 13. Registration at the N^{16} instrument recorder of reactor operation.

will cause $\emptyset_f$ to change by the factor $\frac{1}{F}$, however, this variation in $\emptyset_f$ is compensated only partially by the simultaneous variation in $\tau = \frac{V_c}{Q}$ since the activity of the coolant varies linearly with $\emptyset_f$ and exponentially with τ. At DR 2 the present core is close to its equilibrium size and only minor changes, which do not require a recalibration, are anticipated.

Likewise, abnormal variations in temperature level will necessitate a recalibration. The associated changes in the density of the water amounts to app. 0.035% per ^oC, which will influence the calibration of the instrument since the water density enters the expression for the specific activity of the coolant (eq. 1) through N_o and $\emptyset_f$. A calculation has shown that the influence of temperature variations upon the calibration of the N^{16} instrument amounts to app. 0.02% per ^oC.

Due to the time it takes the coolant to flow from the core to the scintillation counter, the N^{16} instrument will register a change in power level with a certain time delay (app. 10 seconds). This time delay will cause only negligible error in the indication of total MW-hours at the power integrating counter during start up of the reactor, and the error will be cancelled during the next shut-down of the reactor.

In order to obtain a sufficiently stable indication of reactor power level by the ratemeter and recorder of the N^{16} instrument, it has been necessary to use a time constant of 50 seconds at the ratemeter. Fig. 13 shows the registration at the recorder for a short-time of reactor operation, including a start-up and a quick shut-down ("Scram").

Due to the heavy shielding around the scintillation probe and the high energy discrimination at the pulse-height analyzer, the error in the indication of integrated reactor power arising from "background"-counts amounts to only app. 3000 counts or 0.03 MW-hours per 24 hours and is, therefore, negligible.

Having the features as described above, the power measuring instrument, which has been installed at DR 2, based upon measurement of the N^{16} activity of the coolant has proved to give an indication of reactor power level, for all practical purposes independent of other system variables. Therefore, in this aspect the N^{16} instrument is much superior to the conventional type of power instruments with ionization chambers. However, due to the time delay of power signal from the instrument, it is generally not advisable to utilize this signal to activate a fast-acting safety channel.

The power integrator in particular has been very reliable and extremely useful for the daily work on a research reactor like DR 2, since it gives an immediate answer to the questions of fuel burn up and integrated doses for irradiations in the reactor.

The N^{16} power measuring instrument has now been incorporated as a permanent part of the DR 2 instrumentation.

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